

Flavor aspects of parton energy loss

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Abstract

Understanding flavor dependence of the parton energy loss is one of key tasks of the jet quenching physics. In these proceedings we provide a summary of recent works on a quantification of the flavor dependence of parton energy loss along with a summary and discussion of a subset of contributions presented at the Hard Probes 2016 conference which are related to the flavor aspects of parton energy loss.

Keywords: heavy ion collisions, parton energy loss, jet quenching, color factor, flavor

1. Introduction

Understanding flavor dependence of the parton energy loss is one of key tasks of the jet quenching physics. The original results presented in these proceedings are largely based on Refs. [1, 2] that put forward a model or method which allows to quantify some of the basic properties of the parton energy loss. Besides that, we included here also a summary and discussion of a subset of contributions presented at the conference which are related to the flavor aspects of the parton energy loss and we include also an outcome of some of discussions which took place at the conference.

This paper is organized as follows: in the first section we discuss basic features seen in the data on inclusive charged particles and jets in Pb+Pb collisions at the LHC and relate them with the flavor dependence of the parton energy loss. In the second section we put forward a quantification of the flavor dependence of the parton energy loss and provide further discussion on the impact of the flavor dependence on dijet measurements, jet substructure measurements, and measurements employing charged particles. In the last section we discuss the latest results on charmonia in the kinematic domain of large- p_T and we point to a similarity between the jet quenching and charmonia suppression which indicates that radiative energy loss may be a dominant source of the energy loss of charmonia at high- p_T .

2. Suppression of inclusive charged particles and jets at the LHC

Many precise measurements of the suppression of inclusive charged particles quantified using the nuclear modification factor, R_{AA} , have been published by LHC experiments [3–6]. Direct quantification of the magnitude of parton energy loss using the charged particle R_{AA} is not straightforward since the correspondence between the kinematics of the initial parton and observed final state hadron is smeared by the fragmentation process. Consequently, more direct quantification of the parton energy loss may be done from the measurements of jet R_{AA} . At this conference a new result on the R_{AA} of fully reconstructed jets with different jet sizes has been presented [7]. This new measurement follows the previously measured jet R_{AA} [8]. Complementary to these measurements is the measurement of fragmentation functions which was presented at this conference by several speakers and which was published in Refs. [9–11].

The above cited results bring questions about some interesting features seen in the data:

- *Why do have the jet R_{AA} and charge particle R_{AA} almost no rapidity dependence given different input parton spectra and flavor composition at different rapidities?*
- *What is responsible for the enhancement at high momentum fractions (z) seen in the fragmentation? Can we find a connection among charged particle R_{AA} , jet R_{AA} and jet fragmentation measurement?*

- Having the jet R_{AA} at hand can we directly quantify the size of the parton energy loss?

To answer these questions we introduced a model [1] which is based on parameterizations of initial parton spectra and the parton energy loss. The only assumption on the physics of the jet quenching in this model is the functional form for the parton energy loss which is assumed to be of the power-law form – the total transverse momentum lost by the parton is

$$\Delta p_T = c_F \cdot s \cdot \left(\frac{p_{T,ini}}{p_{T,0}} \right)^\alpha \quad (1)$$

Here s , α , and c_F are free parameters of the model, $p_{T,ini}$ is the transverse momentum of a parton initiating a jet and $p_{T,0}$ is an arbitrary scale (set to 40 GeV). Parameter c_F represents a color factor which quantifies the difference between the in-medium radiation of quark-initiated jets and gluon-initiated jets. For the first studies, the c_F was fixed to be 1 and $C_A/C_F = 9/4$ for light-quark-initiated jets and gluon-initiated jets, respectively.

For a better orientation we label this our approach Effective Quenching (EQ) model but it could very well be called *the model independent method* which allows to extract basic properties of the average parton energy loss.

The EQ model is capable of describing the full p_T^{jet} , rapidity, and centrality dependence of the measured jet R_{AA} using three effective parameters which are obtained by minimizing with respect to the R_{AA} data published in Ref. [8]. The successful description of the jet R_{AA} in the full kinematic space implies that the absence of a clear rapidity dependence seen in the data comes from a cancellation between two competing effects which evolve with increasing rapidity: steepening of initial parton spectra and enhancing the fraction of quark initiated jets. While the former alone generally leads to a smaller R_{AA} the later alone generally leads to a larger R_{AA} .

The quantification of the average parton energy loss provided by minimizing the difference between the model and the data revealed three interesting properties of the energy loss: 1) the magnitude of the energy loss, s , depends linearly on the N_{part} ; 2) the power α is approximately 0.5 and it is constant as a function of N_{part} ; 3) the linear dependence of s on N_{part} does not extrapolate to zero for N_{part} approaching zero. For more details on this quantification see Refs. [1, 2].

The model can be further used to evaluate the impact of the change in the jet spectra on the measured fragmentation functions in a simple way. The main principle of the procedure is following: subtract the energy from the initial parton and then let it fragment as in the vacuum. The modifications of fragmentation functions were quantified in the data e.g. by a ratio, $R_{D(z)}$, of fragmentation functions measured in central collisions to those measured in peripheral or proton-proton collisions. The modifications seen from $R_{D(z)}$, excluding the enhancement at low- z , are described by the model. Thus, it may be concluded that these modifications result primarily from the different quenching of the quark and gluon jets. The assumption on the fragmentation of the quenched parton used here reflects a physics scenario in which the parton shower loses the energy coherently. Indeed, it was recognized in several theoretical papers that such color coherence effects play an important role in the jet quenching process [12–15]. The successful description of the jet fragmentation when employing this assumption within EQ model may be considered an independent argument speaking in favor of the physics scenario based on the color coherence.

The charged particle R_{AA} and jet R_{AA} can in principle be connected using fragmentation functions since each charged particle with sufficiently high- p_T which does not come from the underlying event has to be found in a jet. The fact that the model can reasonably well reproduce the R_{AA} of inclusive charged particles at $p_T \gtrsim 20$ GeV is a cross-check. Besides that, it answers a question which was posed several times at this conference: *How to reconcile the fact that the charged particle R_{AA} reaches values greater than the values of R_{AA} of inclusive jets?* The answer to that question is that such a direct interpretation of the charged particle R_{AA} is not possible since charged particle R_{AA} is a non-trivial convolution of flavor dependent jet suppression and fragmentation functions. The fact that the EQ model can reproduce all three kinds of jet related measurements implies that the data do not contradict each other.

It should be mentioned that the advantage of the above described modelling is that it allows to obtain exact analytic formulae for the R_{AA} and $R_{D(z)}$ which can then be used in a straightforward way to extract information about the modification of jet yields and jet structure. Another advantage is that the model employs *minimal* assumptions on the physics of the jet quenching. While this may

be judged as an advantage it may also be judged as a disadvantage since we explore here just the *average* jet quenching ignoring e.g. the path-length dependence of the quenching or the role of fluctuations in the jet quenching. On the other hand, if the model fails in describing some observable, it allows to quantify the impact of these effects on that observable as discussed in the next section.

There are several predictions that can be made based on this modelling:

1. Jet R_{AA} should start to decrease at forward rapidities.
2. If the magnitude of the energy loss is the same in 2.76 TeV and 5.02 TeV Pb+Pb collisions, then the jet R_{AA} measured at 5.02 TeV should be very similar to the R_{AA} measured at 2.76 TeV.
3. The enhancement observed in $R_{D(z)}$ distributions for fragments with high- z should be smaller for more forward jets.
4. $R_{D(z)}$ distributions for fragments with z approaching one should start to decrease.

In particular prediction 3) and 4) appears to be seen in the new precise data shown at this conference [11].

3. Quantifying the role of the flavor

Given the quantification of the energy loss of inclusive jets provided in the previous section, more questions can be asked:

1. *Can we quantify a difference between the jet quenching of light-quark jets and b-jets?*
2. *Can we quantify the color-charge dependence of the jet quenching?*
3. *What observables are sensitive to the difference between the quenching of quark and gluon initiated jets?*

To answer the first question we can compare the b-jet quenching simulation with the data from Ref. [16]. The b-jet quenching simulation used the EQ model which was first run with the assumption that the b-jet energy loss is the same as the energy loss of light quark jets. Then energy loss was increased in steps and the result was compared with the data as shown in Fig. 1. By minimizing the difference between the data and the simulation, it was found that the b-jets are quenched 1.5 ± 0.4 times more than the light-quark jets. The evaluation of

this relative suppression assumes that $30\% \pm 10\%$ of b-jets are produced in the gluon splitting [16] for which the gluon jet suppression is used.

The second question seeking for the quantification of the difference between the in-medium radiation of quark and gluon jets is one of the basic questions of the jet quenching physics. The knowledge of the color-charge dependence of the parton energy loss should provide a direct link between the in-medium parton radiation and basics of the pQCD represented at the leading order by SU(3) Casimir invariants C_A and C_F . Attempts and proposals were put forward to extract that difference using identified charged particles in past, see e.g. Refs. [17, 18]. However, no direct extraction of the color factor in heavy ion environment existed as of now. To extract the color factor, more precise quantification of the quenching of inclusive jets was done using a global fit and the modeling of the initial parton spectra using precise NLO description as described in [2]. This allowed to extract the color factor which quantifies the difference between the in-medium radiation of quark-initiated jets and gluon-initiated jets. The value $c_F = 1.78 \pm 0.12$ was obtained. This value is consistent with the value calculated and measured in the vacuum which is ≈ 1.8 at the jet hardness $Q = 100$ GeV [19, 20].

While the information about the color-charge dependence of the jet quenching is interesting by itself, the fact that quark and gluon initiated jets are suppressed differently implies that certain observables aiming to quantify modifications of the jet substructure or a path-length dependence of the jet quenching can be biased by this basic feature of the parton energy loss. Specifically at this conference two new measurements were discussed: the measurement of the splitting distribution z_g [21] and the measurement of the dijet asymmetry distribution [22]. The former measurement can be used to access the modifications of the jet internal structure at the level of subjets, the later measurement can be used to quantify e.g. the path-length dependence of the jet quenching or to access the role of the fluctuations in the jet quenching. By employing the EQ model and checking the behaviour of observables in POWHEG+PYTHIA8 [23–25] simulation, it was concluded that the z_g distributions are not sensitive to flavor of initial partons and that asymmetry distributions exhibit only a modest sensitivity to the flavor. To build a basic knowledge about sensitivity of the dijet asymmetry to processes that go beyond the average energy loss we use the EQ

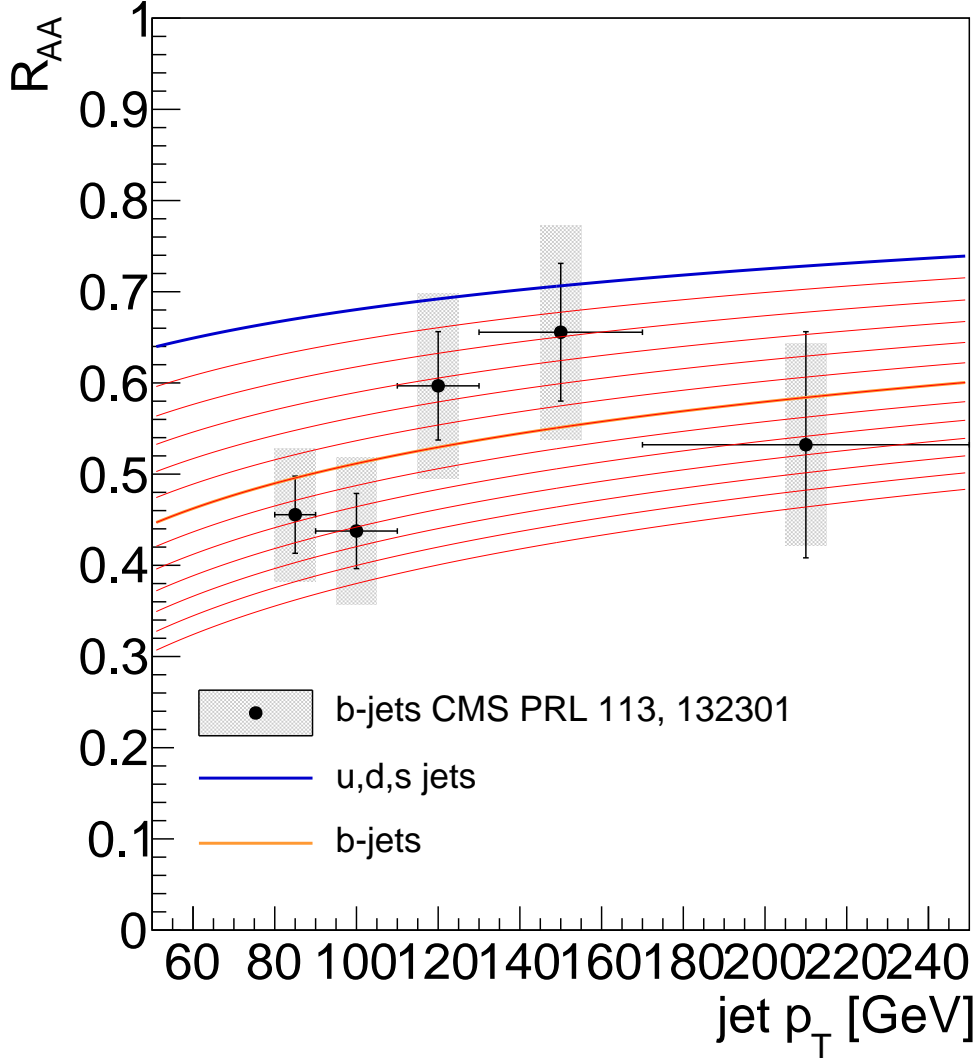


Figure 1: Evaluation of the difference between the quenching of light-quark initiated jets and b-quark initiated jets within the EQ model. Blue line represents the energy loss of b-jets for the case that they are suppressed by the same magnitude as the light-quark initiated jets. Orange lines represent multiples of light quark suppression which are inputs to the determination of the minimal difference between the simulation and the data. Thick orange line represents a result of the minimization (for details see the text).

model to calculate a difference between the leading and subleading jet quenching which is needed to reproduce the data. It was found that in order to reproduce the maximum seen in the measured asymmetry distribution in 0-10% central collisions for leading jets with $p_T = 100 - 126$ GeV, the subleading jet needs to be quenched three times more on average than the leading jet.

The conclusion about no or weak sensitivity of the splitting and dijet asymmetry distributions on

the initial parton flavor does not obviously hold e.g. for the p_T spectra of inclusive charged particles which are emitted from different partons at different transverse momenta or center of mass energies. This is one aspect which is more or less obvious but important and which needs to be taken into account e.g. when comparing the magnitude of inclusive charged particle R_{AA} at RHIC and at the LHC. Another aspect which is also more or less obvious and which needs to be considered for such compar-

isons is the difference in the slopes (and shapes) of initial parton spectra. This may be put into the context of the discussion about the puzzling difference of the size of K-factors quantifying the magnitude of the jet quenching which appear to be larger at RHIC than at the LHC, see Ref. [26], which was also briefly discussed at this conference. Indeed, when using precise NLO initial parton spectra for RHIC and LHC energies along with the same magnitude of the parton energy loss as an input to the EQ model, one obtains larger values of R_{AA} for LHC energies than for RHIC energies which might be interpreted at a first glance as a larger quenching at RHIC than at the LHC. The judgment about these biases which might appear in some studies of the jet quenching are left for respective authors. The discussion presented here only aims to draw the attention to these flavor related aspects of the jet quenching which calls for an explicit treatment (see e.g. Ref. [27]).

4. Radiative energy loss of charmonia

The ability of EQ model to successfully describe jet R_{AA} in all measured rapidity bins, inclusive charged particle R_{AA} at high- p_T , and details seen in the inclusive jet fragmentation functions, which was discussed in the Sec. 2, speaks strongly in favor of a physics picture in which parton shower or its large part loses the energy coherently. If the parton shower, or its large part, radiates as one object, one can ask if it is possible to find some similarities between the suppression of jets and a suppression of other objects with an internal structure. One such candidate are the charmonia. The similarity between the jet suppression and charmonia suppression was explored in Ref. [2] and it is briefly summarized here in the context of other results presented at this conference.

There is no unique interpretation of the charmonia suppression measurements as of now [28]. New measurements at the LHC [29–34] should provide more insight to the mechanism of the charmonia suppression. The precise measurements of the prompt J/ψ in the muon channel [30, 34] showed that the nuclear modification factor, $R_{AA}^{J/\psi}$, reaches a value of ~ 0.2 in the most central collisions ($N_{\text{part}} \gtrsim 350$), continuously grows up to a value of $\sim 0.6 - 0.7$ reached in the most peripheral collisions ($N_{\text{part}} \lesssim 50$). The $R_{AA}^{J/\psi}$ exhibits only a weak (if any) dependence on the J/ψ momentum in the re-

gion of $p_T = 6.5 - 30$ GeV and $|y| < 2.4$. The dependence of $R_{AA}^{J/\psi}$ on the rapidity is also weak. More recently, a prompt production of $\psi(2S)$ was also measured in terms of a double ratio of measured yields, $(N_{\psi(2S)}/N_{J/\psi})|_{\text{Pb+Pb}}/(N_{\psi(2S)}/N_{J/\psi})|_{pp} = R_{AA}^{\psi(2S)}/R_{AA}^{J/\psi}$ [32]. It was shown that $\psi(2S)$ yields are suppressed by a factor of ~ 2 with respect to J/ψ in the range $|y| < 1.6$ and $6.5 < p_T < 30$ GeV. At this conference, also new results were shown on the charmonia suppression in 5.02 TeV Pb+Pb data measured by ATLAS [35] and CMS [36] where quantitatively similar trends in the charmonia suppression to those in 2.76 TeV data were observed.

To test the idea of similarity in the physics of jet quenching and prompt charmonia suppression the EQ model has been employed. The input to the model were p_T spectra of J/ψ and $\psi(2S)$ and effective parameters obtained from the analysis of jet R_{AA} . The p_T spectra were obtained from PYTHIA8 which was reweighted to reproduce the data measured in pp collisions at the 2.76 TeV [37]. The realistic p_T spectra were then used as an input to the EQ model which was run with two different settings of the color factor: first, corresponding to the color factor for the energy loss of light-quark initiated jets (defined to be one), and second, corresponding to the color factor extracted for the energy loss of gluon-initiated jets. A very good agreement of the model with the data for the case of the light-quark energy loss was seen. The N_{part} dependence of $R_{AA}^{J/\psi}$, its p_T and rapidity dependence were reproduced. Remarkably, the model was also able to very well reproduce the suppression of $\psi(2S)$ from Ref. [32] which was quantified in terms of the ratio of nuclear modification factors, $R_{AA}^{\psi(2S)}/R_{AA}^{J/\psi}$. The striking similarity between the measured J/ψ and $\psi(2S)$ suppression and the energy loss of jets suggests that the radiative energy loss may be a dominant contribution to the energy loss of charmonia in the studied kinematic region.

Quantification of the magnitude of the parton energy loss and the role of the flavor in the parton energy loss along with the observations of the similarity between the jet quenching and charmonia suppression should improve the understanding of physics mechanism behind both, the jet quenching and charmonia suppression.

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